

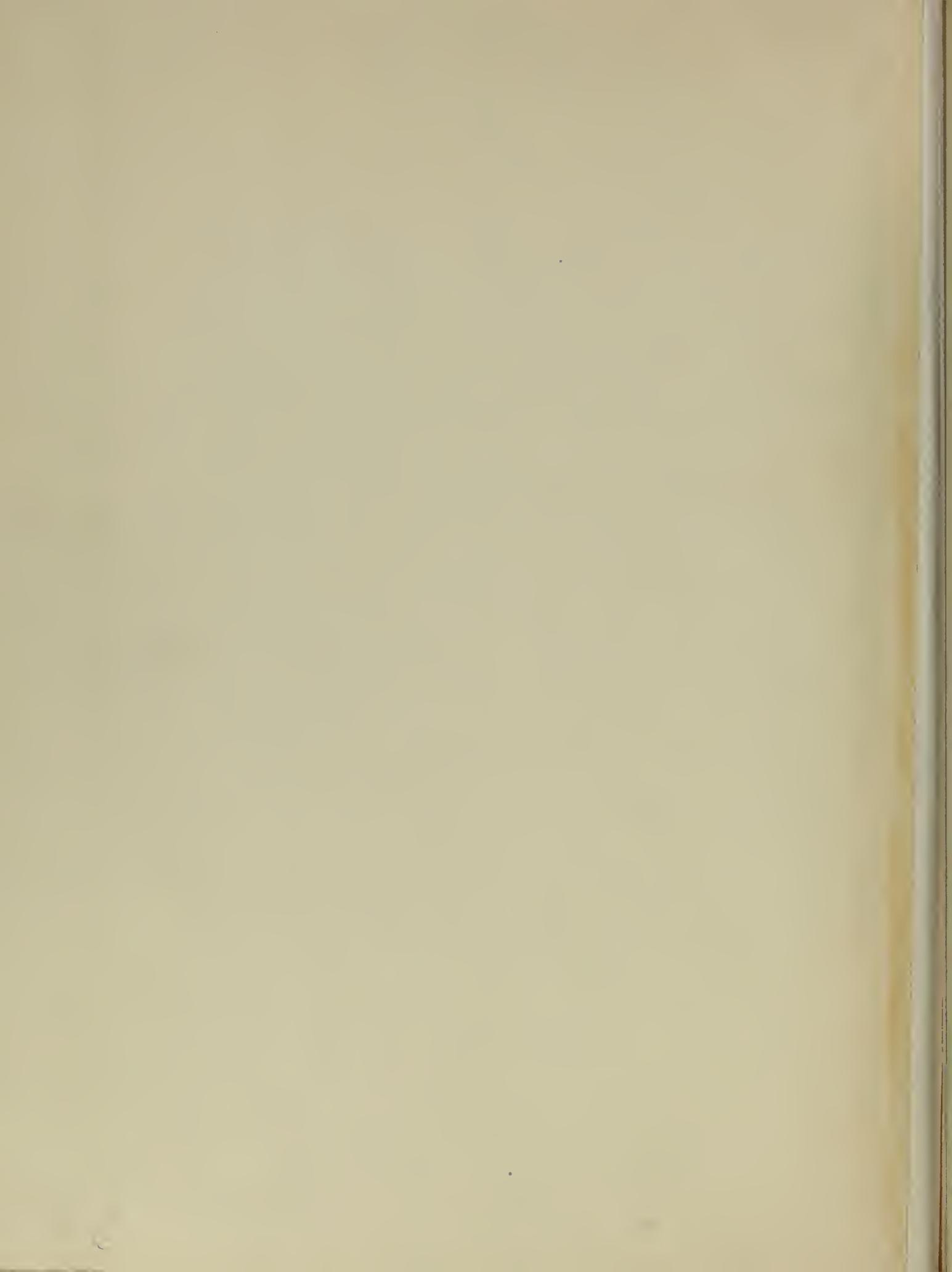
AN INVESTIGATION OF  
THE USE OF INDUCTION  
GENERATORS IN AIRCRAFT  
ELECTRICAL SYSTEMS

BY  
JOHN PEYTON HOBSON

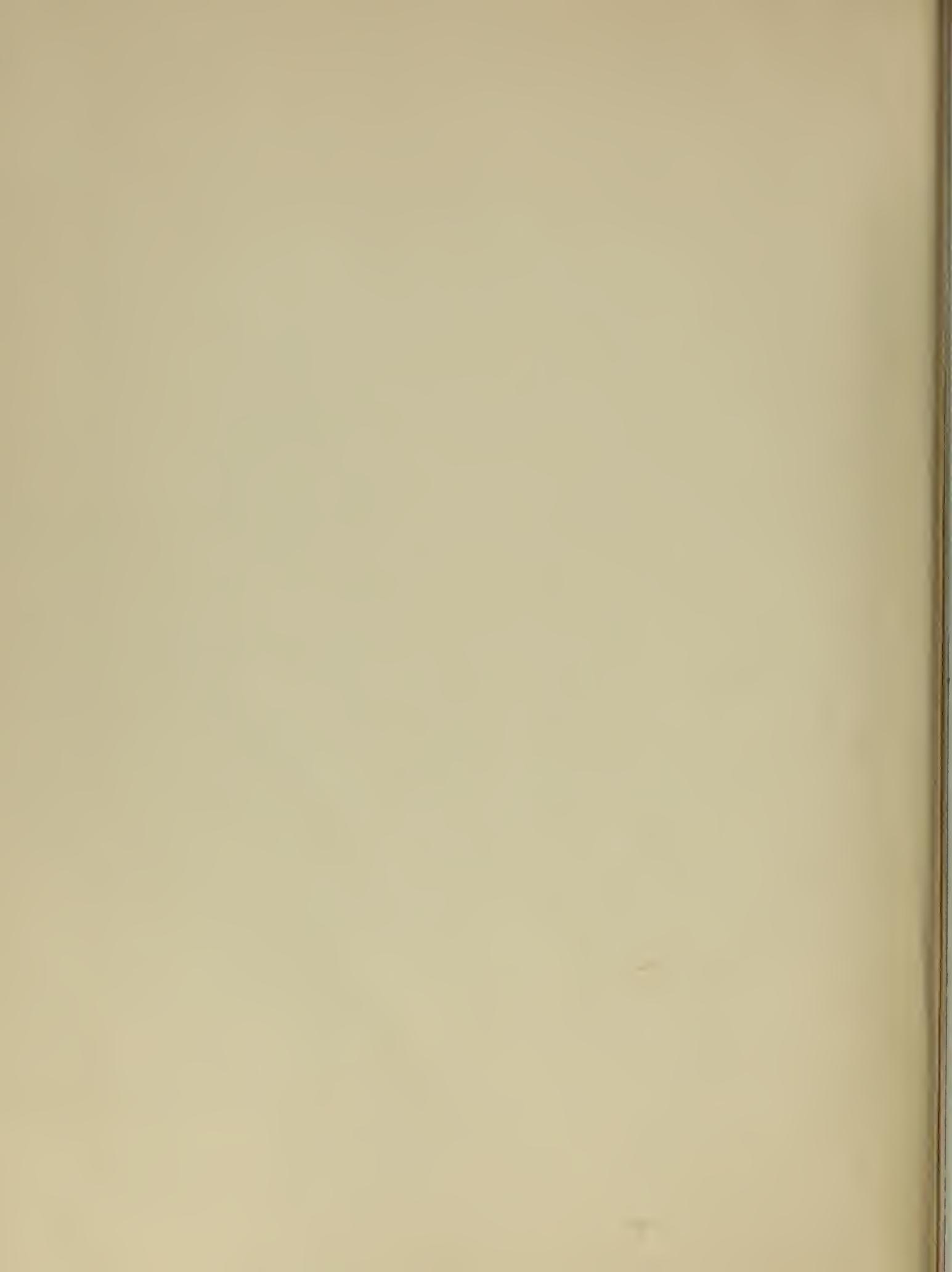
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John Peyton Hobson

Thesis  
Hbk

AN INVESTIGATION OF THE USE OF INDUCTION  
GENERATORS IN AIRCRAFT ELECTRICAL SYSTEMS

by

John Peyton Hobson,  
Lieutenant Commander, United States Navy

Submitted in partial fulfillment  
of the requirements  
for the degree of  
MASTER OF SCIENCE  
in  
ELECTRICAL ENGINEERING

United States Naval Postgraduate School  
Annapolis, Maryland  
1951

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This work is accepted as fulfilling  
the thesis requirements for the degree of

MASTER OF SCIENCE

in

ELECTRICAL ENGINEERING

from the

United States Naval Postgraduate School



## PREFACE

This paper is a theoretical investigation of the practical use of induction generators in 3 phase 400 cycle aircraft electrical systems. No particular installation was intended although the generator capacity is on the order of new machines currently being developed for use in the near future.

Since no induction motors of the power and frequency ratings desired are at present in existence such a machine was designed. However, only the electrical part of the design was considered although reasonable estimates of total weight and dimensions were necessary.

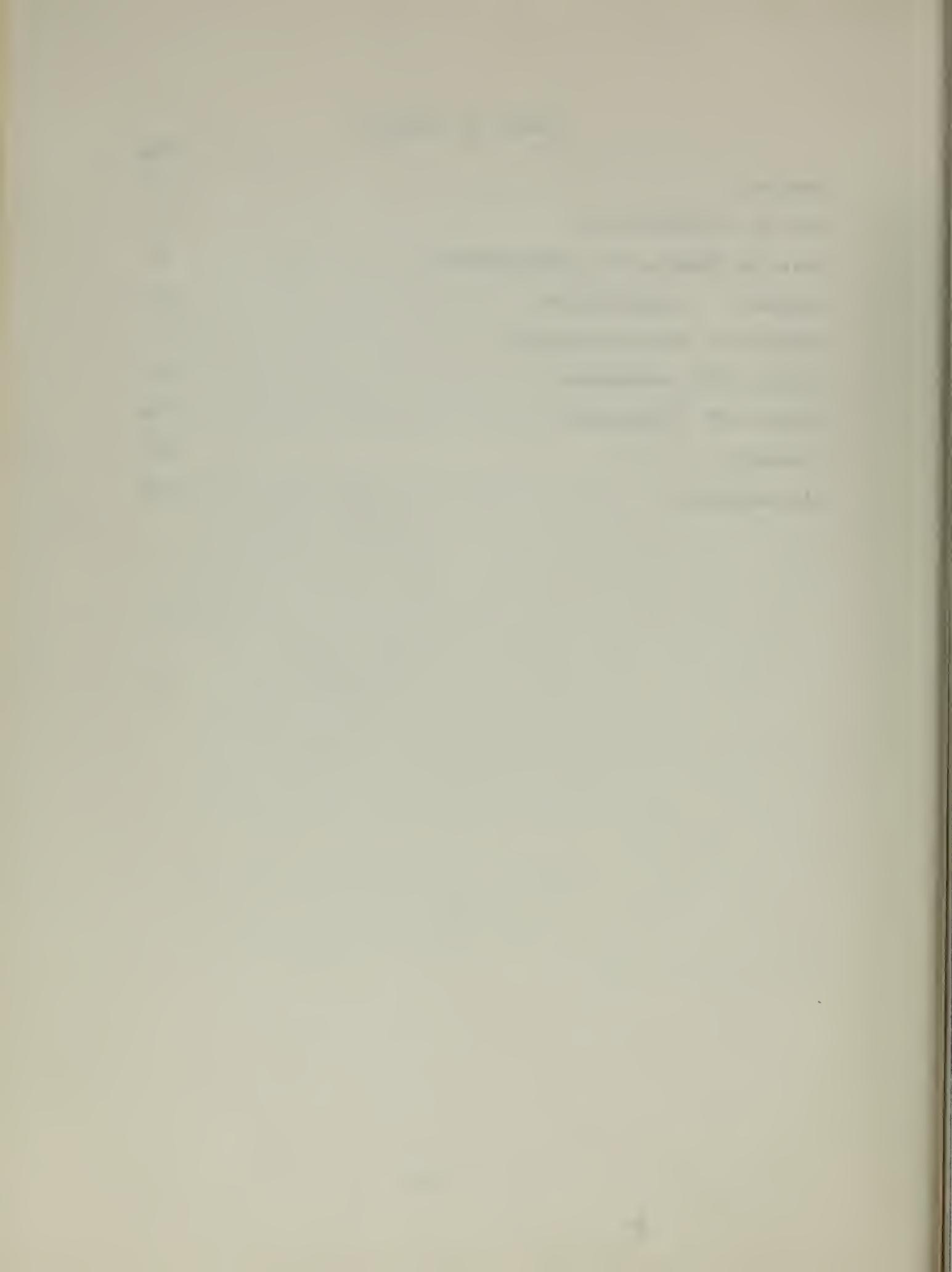
It is the author's desire to acknowledge the assistance given by Professors C.V.O. Terwilliger and W.C. Smith and to thank collectively the members and students of the Electrical Engineering Department of the Postgraduate School.

This work was performed between December 1950 and June 1951 at the United States Naval Postgraduate School, Annapolis, Maryland.



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TABLE OF SYMBOLS AND ABBREVIATIONS

|         |                                |
|---------|--------------------------------|
| AT      | Ampere turns                   |
| B       | Magnetic flux density          |
| Bc      | Corrected gap density          |
| Bcl     | Stator core flux density       |
| Bc2     | Rotor core flux density        |
| Bt1     | Stator tooth flux density      |
| Bt2     | Rotor core flux density        |
| E       | Voltage                        |
| f       | fringing constant              |
| H       | Watts /cubic inch/ °Centigrade |
| I       | Current in amperes             |
| I1      | Primary current                |
| I2 = Ib | Secondary current              |
| Iba     | Average secondary current      |
| Irm     | Maximum current in end rings   |
| Ir      | R.m.s. current in end rings    |
| K1      | Slot contraction factor        |
| Kd      | Duct contraction factor        |
| kb      | Belt factor                    |
| kp      | Pitch factor                   |
| l       | Armature length                |
| le      | Equivalent armature length     |
| lc      | Length of end connections      |
| N1      | Number of primary conductors   |
| N2      | Number of rotor bars           |
| Nt      | Number of slots                |



|             |                                      |
|-------------|--------------------------------------|
| n           | Frequency                            |
| 2p          | Number of poles                      |
| p'          | Number of phases                     |
| P' h        | Hysteresis loss; watts /cubic inch   |
| P' e        | Eddy current loss; watts /cubic inch |
| Pk2         | Total watts lost in rotor            |
| r1          | Stator resistance                    |
| r2          | Rotor resistance                     |
| r           | Total resistance (r1 r2)             |
| S           | Slots/phase/pole                     |
| s           | Slip                                 |
| T           | Temperature rise, degrees centigrade |
| Tss         | Starting torque in synchronous watts |
| Ts          | Starting torque in foot-pounds       |
| U           | Perimeter of phase belt bundle       |
| v           | Synchronous peripheral velocity      |
| X           | Total reactance (X1 X2)              |
| X1          | Stator reactance                     |
| X2          | Rotor reactance                      |
| Xm          | Magnetizing reactance                |
| $\lambda_p$ | Pole pitch                           |
| $\lambda_t$ | Tooth pitch                          |
| $\delta$    | Radial depth of air gap              |
| $\phi$      | Total flux                           |
| $\Delta$    | Peripheral current density           |
| a1          | Equivalent stator tooth tip          |
| a2          | Equivalent rotor tooth tip           |
| c           | Conductors per slot                  |



d           Diameter

a<sub>cp</sub>       Coil pitch ÷ pole pitch



## CHAPTER I

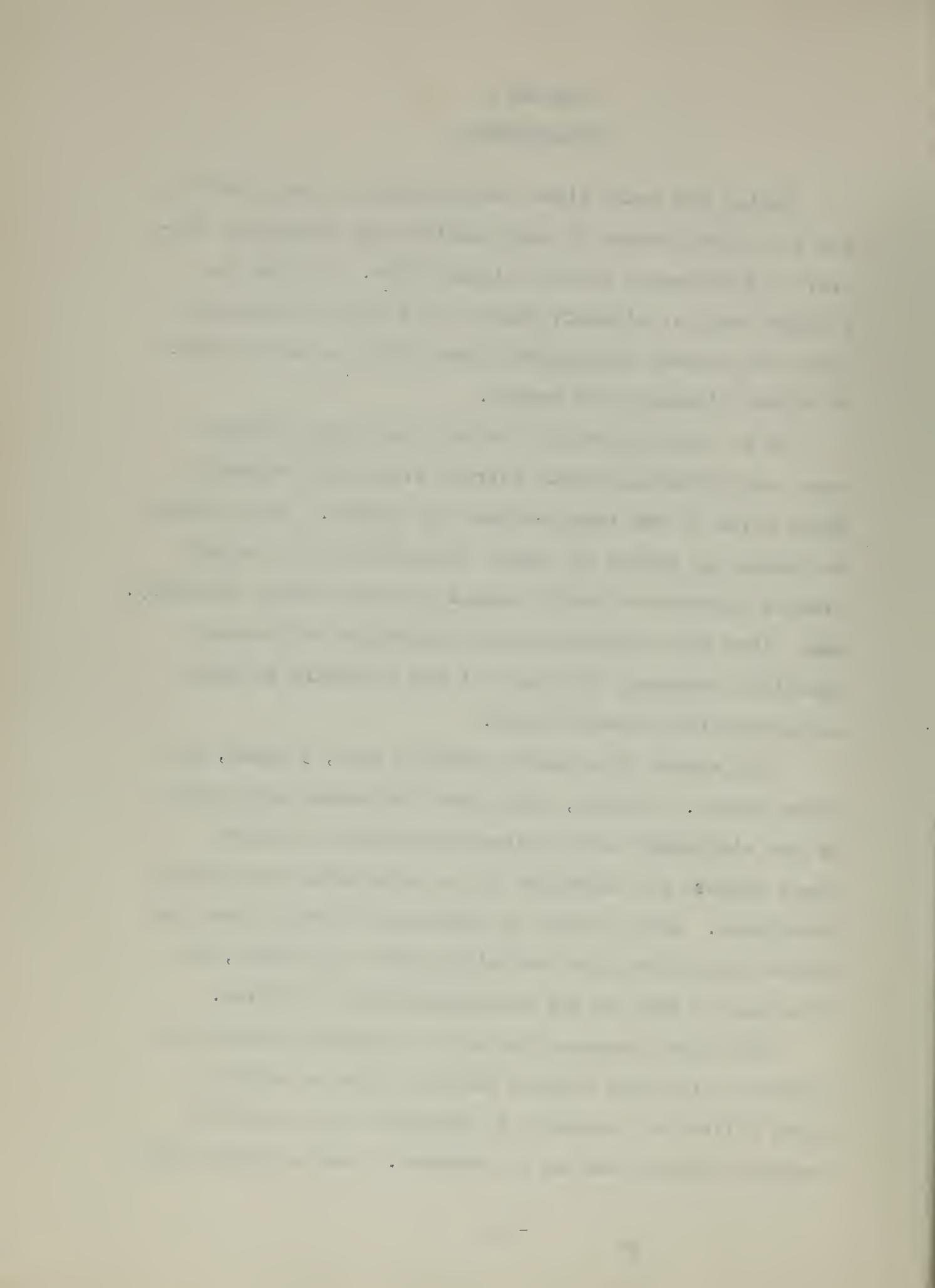
### INTRODUCTION

During the years since the beginning of World War II the electrical demand in both military and commercial aircraft has increased almost without limit. In 1940 the average load per aircraft engine was about two kilowatts while the present contemplated load today is of the order of thirty kilowatts per engine.

Up to the present day aircraft electrical systems have been primarily direct current with major emphasis being given to the twenty-eight volt system. In an effort to reduce the weight of copper conductors and to attain greater generator capacity higher voltages became necessary. And, since high altitudes make commutation and contact operation extremely difficult it was necessary to adopt an alternating current system.

This system is a nominal 208/120 volt, 3 phase, 400 cycle system. However, since the alternators are driven by the airplanes' main engines very precise constant speed drives are necessary if the alternators are to be paralleled. Such a drive is presently in use by both the United States Navy and the United States Air Force, but it weighs as much as the alternator which it drives.

This paper proposes the use of induction generators coupled to the main engines through suitable variable speed drives and connected in parallel with a constant frequency source such as an inverter. Such a system would



have the following advantages:

- (1) The system frequency would be independent of generator speed.
- (2) The generator speed would be determined by the load demand which is more readily sensed than frequency.
- (3) The induction generator with exciting condensers is lighter than an equivalent alternator.
- (4) Since an induction generator has a high rotor resistance to achieve the desired characteristics, it has a high starting torque and so can serve as the main engine starter, thus eliminating that item completely.

Induction generators, on the other hand, have the disadvantage that they will not provide any reactive power. However, it is this author's belief that the weight of copper saved will compensate for the condensers used at the loads to achieve unity power factor.



CHAPTER II  
MACHINE DESIGN

Since no 400 cycle induction motors of large ratings were available with which to conduct tests, the electrical design phase of such a machine was completed. The results of this design follow:

|                                   |                |
|-----------------------------------|----------------|
| Output                            | 40 kw = 53.6HP |
| Phases                            | 3              |
| Terminal voltage                  | 208            |
| Frequency                         | 400            |
| Full load efficiency              | 0.88           |
| Full load power factor (as motor) | 0.92           |
| Armature connection               | Star           |
| Current per phase                 | 137.2          |
| Number of poles                   | 8              |
| Synchronous rpm                   | 6000           |
| Gap density                       |                |
| As motor                          | 23,450         |
| As generator                      | 25,500         |
| Diameter                          | 10 inches      |
| Length                            | 3.93 inches    |
| Pole pitch                        | 3.93 inches    |
| Induced voltage                   |                |
| As motor                          | 115            |
| As generator                      | 125            |
| Total number of slots             | 96             |
| Total number of active conductors | 192            |
| Active conductors per phase       | 64             |
| Peripheral current density        | 839            |



|                                   |           |
|-----------------------------------|-----------|
| Net length of iron                | 3.54      |
| Fraction net iron length          | 0.9       |
| Tooth pitch                       | 0.327     |
| Width of tooth tip                | 0.207     |
| Tooth tip density                 |           |
| As motor                          | 41,200    |
| As generator                      | 44,800    |
| Width of Slot                     | 0.12      |
| Slot opening                      | 0.12      |
| Section primary conductor in c.m. | 25,450    |
| Conductor dimensions              | 0.1 x 0.2 |
| Insulation thickness              | 0.01      |
| Depth of slot                     | 0.5       |
| Slot space factor                 | 0.667     |
| Fraction slot width               | 0.367     |

### Core

|                                  |        |
|----------------------------------|--------|
| Thickness of laminations         | 0.01   |
| Radial depth back of slot        | 1.0    |
| Maximum density                  |        |
| As motor                         | 51,200 |
| As generator                     | 55,600 |
| Outside diameter                 | 13     |
| Volume of core (excluding teeth) | 122.3  |
| Hysteresis watts per cubic inch  |        |
| As motor                         | 2.74   |
| As generator                     | 3.13   |
| Eddy watts per cubic inch        |        |
| As motor                         | 4.2    |
| As generator                     | 4.96   |
| Total watts lost in core         |        |
| As motor                         | 850    |
| As generator                     | 990    |



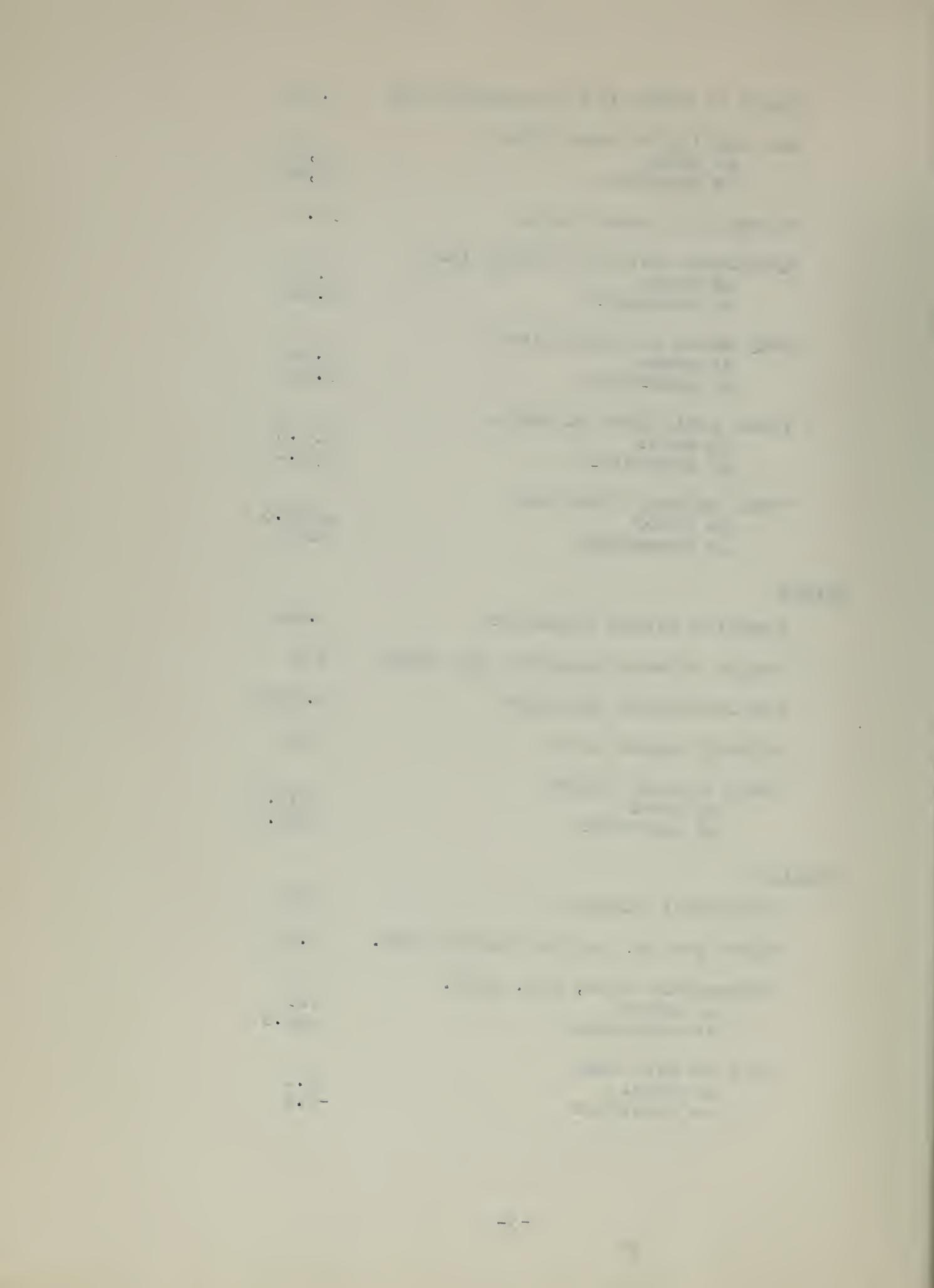
|                                    |        |
|------------------------------------|--------|
| Width of tooth 1/3 from narrow end | 0.214  |
| Max density at same point          |        |
| As motor                           | 39,900 |
| As generator                       | 43,400 |
| Volume of primary teeth            | 34.8   |
| Hysteresis Watts per cubic inch    |        |
| As motor                           | 1.84   |
| As generator                       | 2.02   |
| Eddy watts per cubic inch          |        |
| As motor                           | 2.54   |
| As generator                       | 3.01   |
| Total watts lost in teeth          |        |
| As motor                           | 152.5  |
| As generator                       | 175.0  |
| Total primary iron loss            |        |
| As motor                           | 1002.5 |
| As generator                       | 1165   |

### Copper

|                                    |        |
|------------------------------------|--------|
| Fraction active conductor          | 0.444  |
| Length primary conductor per phase | 566    |
| Hot resistance per phase           | 0.0222 |
| Primary copper loss                | 1255   |
| Total Primary losses               |        |
| As motor                           | 2257.5 |
| As generator                       | 2420.0 |

### Heating

|                                    |       |
|------------------------------------|-------|
| Peripheral Surface                 | 189   |
| Watts per sq. in. per degree cent. | 0.09  |
| Temperature rise, deg. cent.       |       |
| As motor                           | 133   |
| As generator                       | 142.5 |
| Slip at full load                  |       |
| As motor                           | 0.1   |
| As generator                       | -0.1  |



|                        |      |
|------------------------|------|
| Speed at full load     |      |
| As motor               | 5400 |
| As generator           | 6600 |
| Pulley Torque in lb-ft |      |
| As motor               | 52.1 |
| As generator           | 42.6 |

Squirrel Cage Rotor

|                                    |            |
|------------------------------------|------------|
| Number of slots                    | 90         |
| Tooth pitch                        | 0.349      |
| Amperes per slot                   | 256        |
| C.M. per ampere                    | 174        |
| Rotor bar section in C.M.          | 44500      |
| in sq.in.                          | 0.035      |
| Dimensions of bar                  | 0.1 x 0.35 |
| Total depth of slot                | 0.56       |
| Width of slot                      | 0.12       |
| Slot opening                       | 0.04       |
| Width of tooth tip                 | 0.229      |
| Width of tooth 1/3 from narrow end | 0.214      |
| Equivalent length of 1 bar         | 4.0        |
| Total length of bars               | 360        |
| Total watts lost in bars           | 2120       |
| Total watts in rotor conductors    | 4000       |
| Watts lost in end rings            | 1880       |
| Average Amperes per bar            | 231        |
| Max amperes in end rings           | 1300       |
| RMS amperes in end rings           | 919        |
| Total res.of end rings             | .00223     |



|                                 |           |
|---------------------------------|-----------|
| Total length of end rings       | 59.6      |
| Section in c.m                  | 107,000   |
| Section in square inches        | 0.084     |
| Dimensions of end rings         | .24 x .35 |
| Secondary resistance at primary | 0.285     |

### Core

|                                 |       |
|---------------------------------|-------|
| Radial depth back of slots      | 1.0   |
| Maximum density                 |       |
| As motor                        | 51200 |
| As generator                    | 55600 |
| Inside diameter of core         | 7 in. |
| Volume of core excluding teeth  | 89    |
| Secondary frequency             | 40    |
| Hysteresis watts per cubic inch |       |
| As motor                        | .274  |
| As generator                    | .313  |
| Eddy watts per cubic inch       |       |
| As motor                        | .042  |
| As generator                    | .05   |
| Total watts lost in core        |       |
| As motor                        | 28.2  |
| As generator                    | 32.3  |

### Teeth

|                                 |       |
|---------------------------------|-------|
| Max density 1/3 from narrow end |       |
| As motor                        | 42500 |
| As generator                    | 46200 |
| Volume of rotor teeth           | 34.6  |
| Hysteresis watts per cubic inch |       |
| As motor                        | .203  |
| As generator                    | .232  |
| Eddy watts per cubic inch       |       |
| As motor                        | .029  |
| As generator                    | .034  |
| Total watts lost in rotor teeth |       |
| As motor                        | 8.03  |
| As generator                    | 9.2   |



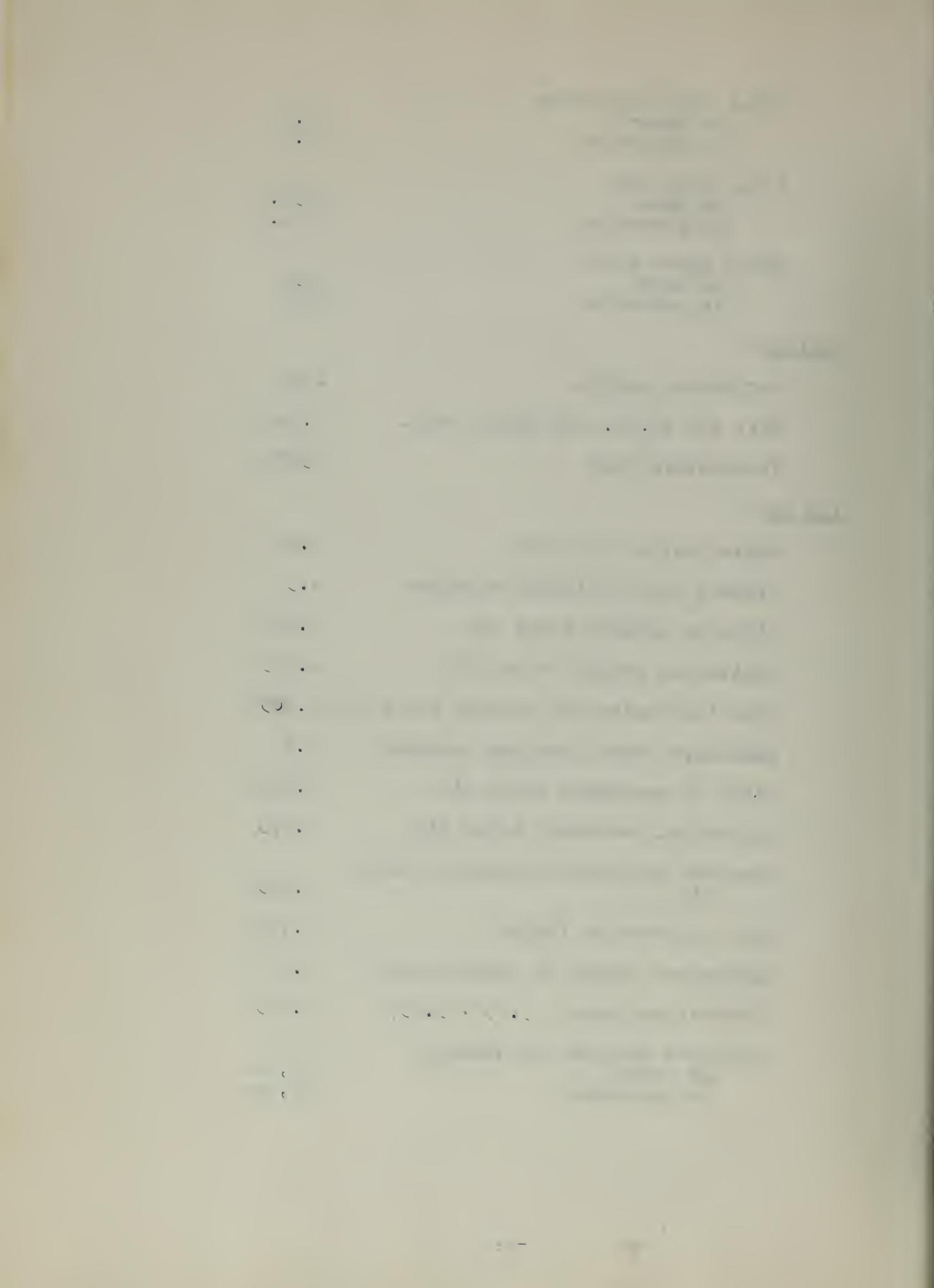
|                       |        |
|-----------------------|--------|
| Total rotor iron loss |        |
| As motor              | 36.23  |
| As generator          | 41.5   |
| Total iron loss       |        |
| As motor              | 1038.7 |
| As generator          | 1206.5 |
| Total rotor loss      |        |
| As motor              | 4036   |
| As generator          | 4041   |

### Heating

|                                  |       |
|----------------------------------|-------|
| Peripheral surface               | 194   |
| Watt per sq.in. per degree cent. | 0.148 |
| Temperature rise                 | 139°C |

### Air Gap

|   |        |
|---|--------|
| Radial depth of air gap                 | 0.02   |
| Primary tooth fringing constant         | 1.3    |
| Width of primary tooth tip              | 0.207  |
| Equivalent primary tooth tip            | 0.263  |
| Fraction equivalent primary tooth tip   | 0.805  |
| Secondary tooth fringing constant       | 0.6    |
| Width of secondary tooth tip            | 0.229  |
| Equivalent secondary tooth tip          | 0.253  |
| Fraction equivalent secondary tooth tip | 0.725  |
| Slot contraction factor                 | 0.584  |
| Equivalent length of armature core      | 3.95   |
| Contraction factor (3.95 + 3.93)        | 1.005  |
| Corrected maximum gap density           |        |
| As motor                                | 40,000 |
| As generator                            | 43,500 |

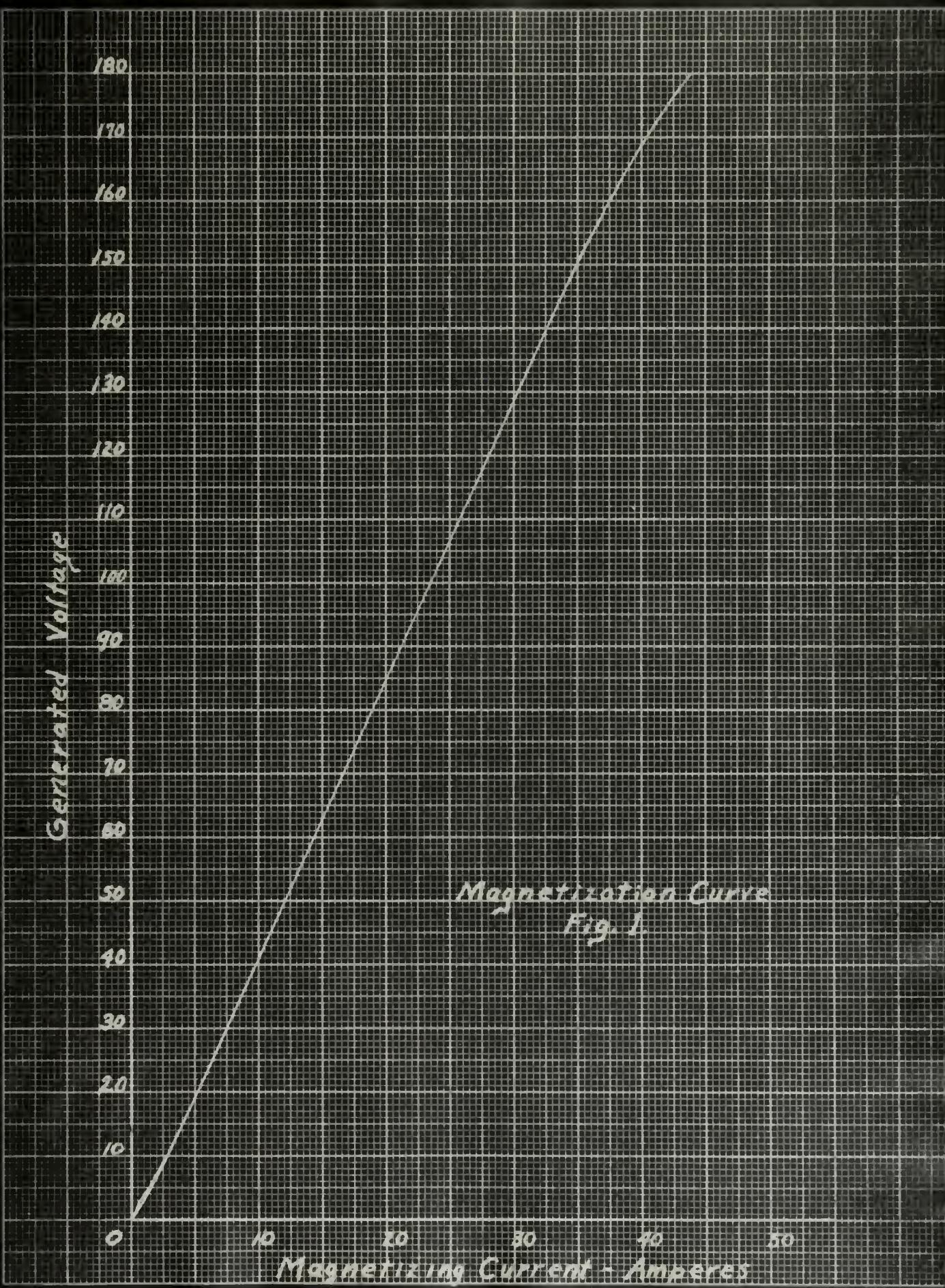


| $E$ | $B_2$ | $A\bar{T}$ | $B_{C1}$ | $A\bar{T}$ | $B_T$ | $A\bar{T}$ | $B_{C2}$ | $A\bar{T}$ | $\Delta t_2$ | $AT$  | $\Delta t_1$ | $AT_r$ | $I_m$ | $X_m$ |
|-----|-------|------------|----------|------------|-------|------------|----------|------------|--------------|-------|--------------|--------|-------|-------|
| 5   | 1740  | 21.8       | 2225     | 3.3        | 1735  | 0.5        | 2225     | 2.6        |              | 1850  | 0.5          | 287    | 1.46  | 3.43  |
| 10  | 3480  | 43.5       | 4450     | 5.0        | 3470  | 0.8        | 4450     | 3.6        |              | 3700  | 0.8          | 57.3   | 273   | 3.67  |
| 20  | 6960  | 87.0       | 8900     | 6.6        | 6940  | 1.1        | 8900     | 4.8        |              | 7400  | 1.1          | 100.6  | 5.11  | 3.91  |
| 30  | 10940 | 130.5      | 13350    | 8.0        | 10410 | 1.3        | 13350    | 5.8        |              | 11100 | 1.3          | 146.9  | 7.46  | 4.02  |
| 40  | 13920 | 174        | 17900    | 9.3        | 13880 | 1.5        | 17800    | 6.8        |              | 14800 | 1.5          | 193.1  | 9.81  | 4.01  |
| 50  | 17400 | 21.5       | 22250    | 10.2       | 17350 | 1.7        | 22250    | 7.4        |              | 18500 | 1.7          | 238.5  | 12.11 | 4.13  |
| 60  | 20880 | 261        | 26100    | 11.2       | 20620 | 1.8        | 26700    | 8.2        |              | 22200 | 1.9          | 284.1  | 14.4  | 4.16  |
| 70  | 24360 | 304.5      | 31150    | 12.1       | 24290 | 1.9        | 31150    | 5.9        |              | 25700 | 2.0          | 322.3  | 16.7  | 4.19  |
| 80  | 27840 | 348        | 35600    | 12.9       | 27760 | 2.1        | 35600    | 9.4        |              | 29600 | 2.1          | 374.5  | 19.0  | 4.21  |
| 90  | 31320 | 391.5      | 40050    | 13.7       | 31230 | 2.2        | 40050    | 10.0       |              | 33300 | 2.3          | 422.7  | 21.3  | 4.22  |
| 100 | 34800 | 435        | 44520    | 14.3       | 34700 | 2.3        | 44500    | 10.4       |              | 37000 | 2.4          | 464.4  | 23.6  | 4.24  |
| 110 | 38280 | 478.5      | 48950    | 14.8       | 38110 | 2.4        | 48950    | 10.8       |              | 46700 | 2.5          | 507.0  | 25.6  | 4.26  |
| 120 | 41760 | 522        | 52440    | 15.9       | 41640 | 2.5        | 52440    | 11.2       |              | 51400 | 2.6          | 533.7  | 26.1  | 4.28  |
| 130 | 45240 | 565.5      | 57850    | 16.0       | 45110 | 2.6        | 57850    | 11.7       |              | 48900 | 2.7          | 592.5  | 30.4  | 4.29  |
| 140 | 48720 | 609        | 62300    | 16.5       | 48550 | 2.7        | 62300    | 12.0       |              | 57800 | 2.8          | 643.0  | 32.6  | 4.29  |
| 150 | 52200 | 652.5      | 66750    | 17.1       | 52050 | 2.8        | 66750    | 12.5       |              | 55500 | 2.9          | 687.8  | 34.9  | 4.27  |
| 160 | 55600 | 696        | 71200    | 20.4       | 55520 | 2.9        | 71200    | 14.8       |              | 59200 | 3.0          | 737.1  | 37.4  | 4.22  |
| 170 | 59100 | 739.5      | 75650    | 27.5       | 58990 | 3.0        | 75650    | 20.0       |              | 62900 | 3.0          | 782.0  | 40.3  | 4.10  |
| 180 | 62600 | 783        | 80500    | 44         | 62460 | 3.1        | 80500    | 32         |              | 66400 | 3.1          | 865.1  | 43.9  | 3.95  |
| 190 | 66000 | 826.5      | 84550    | 66         | 65930 | 3.2        | 84550    | 49         |              | 70300 | 3.2          | 946.9  | 48.1  | 3.92  |
| 200 | 69600 | 870        | 89000    | 88         | 89100 | 3.7        | 89000    | 64         |              | 94200 | 4.0          | 1019   | 52.3  | 3.83  |

Magnetization Data

Table I







WILFRED & ELSIE CO., INC., No. 900 - 3500-12  
10 X 10 for 100% inch. Sta. Dura laminated.  
Cover U.S.A.

Crest Dragon  
Cap 2



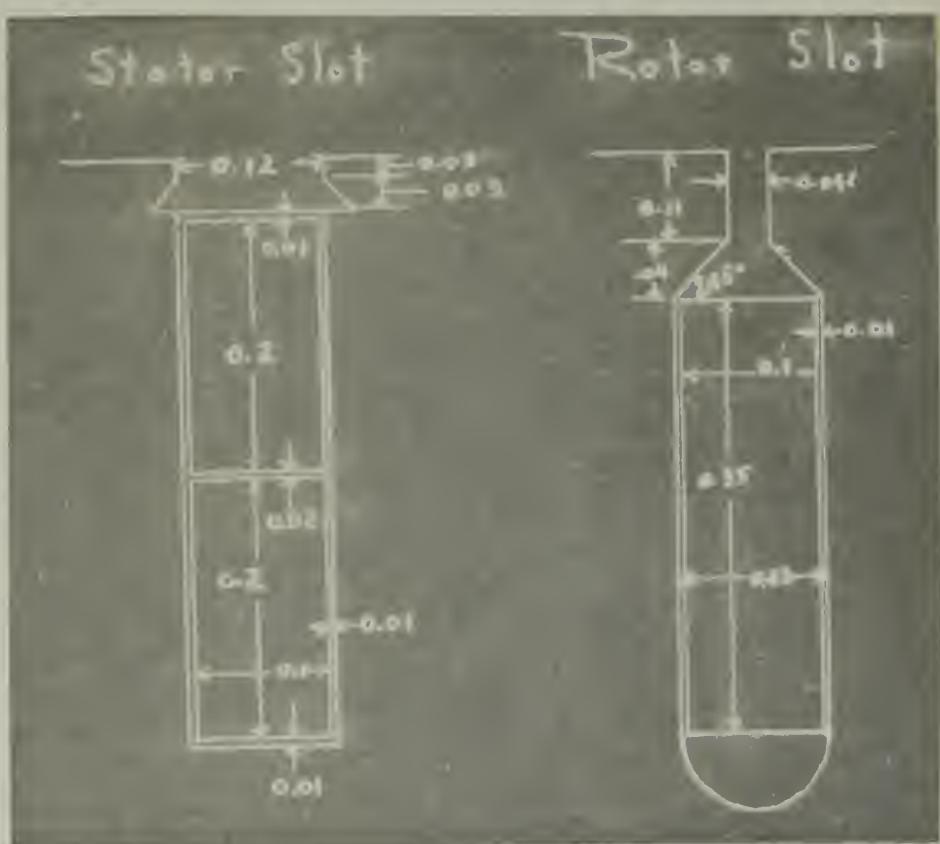
### Constants

|                      |        |
|----------------------|--------|
| Exciting reactance   | 4.27   |
| Exciting resistance  | 35.8   |
| Primary resistance   | 0.0222 |
| Secondary resistance | 0.285  |
| Total resistance     | 0.3072 |
| Primary reactance    | 0.0716 |
| Secondary reactance  | 0.0152 |
| Total reactance      | 0.0868 |
| Leakage factor       | 0.0199 |

### Breakdown and Starting

|                            |                    |
|----------------------------|--------------------|
| Slip at breakdown          | 3.18               |
| Starting current           | 376                |
| Starting torque            |                    |
| Synchronous watts          | 120,000            |
| Pound feet                 | 140                |
| Volume primary conductor   | 11.32 cubic inches |
| Volume rotor bars          | 12.6               |
| Volume rotor end rings     | 5.01               |
| Volume all copper          | 28.93              |
| Weight all copper          | 9.29 pounds        |
| Volume stator core         | 122.3 cubic inches |
| Volume stator teeth        | 34.8               |
| Volume rotor core          | 89.0               |
| Volume rotor teeth         | 34.6               |
| Volume all iron            | 280.7              |
| Weight all iron            | 79.7 pounds        |
| Weight all active material | 89 pounds          |





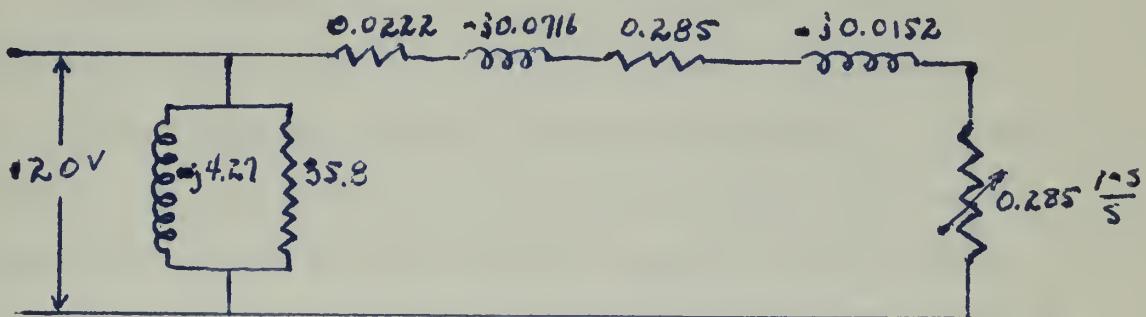


Weight inactive material (estimated) 9  
Total weight 98 pounds



## CHAPTER III PERFORMANCE

Although the important part of the circle diagram of this machine is included in this chapter (fig.2) its size precludes its use in determining the performance. Therefore, the performance of the machine as a generator has been calculated from the constants of the machine. All calculations were made using the following equivalent circuit:



For selected values of slip between -0.005 and -0.4 the current,  $I_{cba}$ , in the secondary necessary for a phase voltage of 120 volts was determined. Using this current the generated voltage was then calculated and the corresponding values of the exciting current taken from the magnetization curve.

The variable resistive losses in the rotor and stator were added to the assumedly fixed iron losses to determine the overall efficiency. The output power current is the secondary current less the fixed core loss current.

Using the exciting current, the secondary current, and the total reactance the total reactive volt amperes

and general knowledge of the country of the Landes.  
The author has made a collection of all the  
available material on the subject, and has  
written a history of the country, and  
of the people who have lived there,  
from the earliest times to the present day.  
The book is written in a simple, direct  
style, and is intended for a wide  
range of readers, from the  
general reader to the  
specialist in the field.  
The author has made a  
careful study of the  
history of the Landes,  
and has tried to  
present it in a  
clear and  
interesting  
manner.  
The book is  
well illustrated  
with  
maps  
and  
photographs,  
and  
is  
fully  
referenced.  
The  
author  
has  
also  
written  
a  
number  
of  
articles  
on  
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topics  
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to  
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Landes,  
which  
are  
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in  
the  
book.  
The  
book  
is  
published  
by  
the  
University  
of  
Bordeaux,  
and  
is  
available  
in  
both  
French  
and  
English  
editions.

required by the generator were determined.

Figure 3 is a plot of exciting current, efficiency, load current per phase, and inverter load (assuming unity power factor and 85 microfarads per phase across the generator terminals) plotted against slip.

From Table III it is seen that at rated load of 111 amperes per phase each induction generator requires 16,500 reactive volt amperes in addition to the lagging reactive volt amperes required by the load.

Present Bureau of Aeronautics Standards specify 0.8 lagging power factor for all a.c. loads. This means 30,000 volt amperes for 40 kilowatts of power. In other words, if this machine is to deliver 40,000 watts some other source must provide 56,500 reactive volt amperes.

The recent advancements in the manufacture of barium titanite ceramic condensers makes their use admirably suitable for this purpose. Such condensers can now be fabricated which weigh not more than 0.03 lbs per microfarad or occupy more than 0.07 cubic inches per microfarad.

An aircraft electrical load of 40,000 watts may be reduced to unity power factor by the use of 276 microfarads of capacity which if distributed at the loads should not weigh more than 15 lbs. If this capacity is placed at the load the weight of conductor may be reduced by 20%, a reduction in weight far exceeding the weight of condensers used.



| $S$    | $r_2 \frac{1-s}{s}$ | $r_1 + r_2$ | $r_1 + \frac{r_2}{s}$ | $x_1 + x_2$ | $z$   | $E$ | $I_2$ | $E_2$ |
|--------|---------------------|-------------|-----------------------|-------------|-------|-----|-------|-------|
| - .005 | - 57.3              | 0.307       | - 57                  | 0.087       | 57    | 120 | 2.1   | 12.7  |
| - .01  | - 28.9              | 0.307       | - 28.5                | 0.087       | 28.5  | 120 | 4.21  | 12.6  |
| - .02  | - 14.5              | 0.307       | - 14.2                | 0.087       | 14.2  | 120 | 8.45  | 12.7  |
| - .03  | - 9.18              | 0.307       | - 9.41                | 0.087       | 9.41  | 120 | 12.7  | 12.8  |
| - .04  | - 7.41              | 0.307       | - 7.10                | 0.087       | 7.10  | 120 | 16.9  | 12.5  |
| - .05  | - 5.99              | 0.307       | - 5.67                | 0.087       | 5.67  | 120 | 21.1  | 12.6  |
| - .07  | - 4.37              | 0.307       | - 4.05                | 0.087       | 4.05  | 120 | 29.6  | 12.7  |
| - .10  | - 3.14              | 0.307       | - 2.83                | 0.087       | 2.83  | 120 | 42.4  | 12.8  |
| - .12  | - 2.56              | 0.307       | - 2.35                | 0.087       | 2.35  | 120 | 57    | 12.7  |
| - .15  | - 2.17              | 0.307       | - 1.88                | 0.087       | 1.88  | 120 | 63.8  | 12.8  |
| - .175 | - 1.11              | 0.307       | - 1.60                | 0.087       | 1.60  | 120 | 75.0  | 12.8  |
| - .19  | - 1.11              | 0.307       | - 1.40                | 0.087       | 1.40  | 120 | 85.6  | 12.8  |
| - .25  | - 1.55              | 0.307       | - 1.24                | 0.087       | 1.24  | 120 | 96.8  | 12.8  |
| - .27  | - 1.46              | 0.307       | - 1.11                | 0.087       | 1.11  | 120 | 107   | 12.8  |
| - .35  | - 1.32              | 0.307       | - 1.01                | 0.087       | 1.015 | 120 | 119.2 | 12.8  |
| - .44  | - 1.24              | 0.307       | - 0.91                | 0.087       | 0.91  | 120 | 130.5 | 12.8  |
| - .5   | - 1.16              | 0.307       | - 0.85                | 0.087       | 0.854 | 120 | 140.5 | 12.8  |
| - .55  | - 1.10              | 0.307       | - 0.79                | 0.087       | 0.795 | 120 | 151   | 12.8  |
| - .575 | - 1.045             | 0.307       | - 0.738               | 0.087       | 0.742 | 120 | 161.5 | 12.8  |
| - .4   | - 1.0               | 0.307       | - 0.69                | 0.087       | 0.695 | 120 | 172   | 12.8  |



| S   | I <sub>L</sub> | I <sub>sh</sub> | I <sub>L</sub> | 3I <sub>L</sub> (G15) | R <sub>sh</sub> | P <sub>out</sub> | I <sub>g</sub> |
|-----|----------------|-----------------|----------------|-----------------------|-----------------|------------------|----------------|
| 1   | 4.21           | 3.35            | 0.86           | 16.4                  | 1200            | 309              | 1531           |
| 2   | 7.45           | 2.35            | 5.1            | 65.7                  | 1200            | 1814             | 6086           |
| 3   | 16.7           | 3.35            | 9.35           | 148.5                 | 1200            | 3364             | 4120           |
| 4   | 16.9           | 3.35            | 13.55          | 663                   | 1200            | 4886             | 6160           |
| 5   | 21.1           | 3.35            | 17.75          | 411                   | 1200            | 6394             | 8012           |
| 6   | 29.6           | 3.35            | 26.25          | 807                   | 1200            | 9444             | 11460          |
| 7   | 42.4           | 3.35            | 39             | 1653                  | 1200            | 14064            | 16948          |
| 8   | 51             | 3.35            | 47.6           | 2374                  | 1200            | 17164            | 20360          |
| 9   | 53.0           | 3.35            | 60.4           | 3750                  | 1200            | 21744            | 26100          |
| 10  | 75.0           | 3.35            | 71.6           | 5116                  | 1200            | 15800            | 22200          |
| 11  | 95.1           | 3.35            | 82.2           | 6750                  | 1200            | 19644            | 31600          |
| 12  | 115            | 3.35            | 93.4           | 8610                  | 1200            | 23500            | 42900          |
| 13  | 135            | 3.35            | 104.6          | 10740                 | 1200            | 27784            | 57120          |
| 14  | 155            | 3.35            | 116.1          | 12820                 | 1200            | 31400            | 75200          |
| 15  | 175            | 3.35            | 127.4          | 15300                 | 1200            | 35200            | 91200          |
| 16  | 195            | 3.35            | 138.2          | 17940                 | 1200            | 38900            | 107120         |
| 17  | 215            | 3.35            | 147.6          | 20000                 | 1200            | 53100            | 125120         |
| 18  | 235            | 3.35            | 157.1          | 24000                 | 1200            | 57500            | 142120         |
| 19  | 255            | 3.35            | 167.1          | 28100                 | 1200            | 61700            | 159120         |
| 20  | 275            | 3.35            | 177.1          | 32100                 | 1200            | 65900            | 176120         |
| 21  | 295            | 3.35            | 187.1          | 36100                 | 1200            | 70100            | 193120         |
| 22  | 315            | 3.35            | 197.1          | 40100                 | 1200            | 74300            | 210120         |
| 23  | 335            | 3.35            | 207.1          | 44100                 | 1200            | 78500            | 227120         |
| 24  | 355            | 3.35            | 217.1          | 48100                 | 1200            | 82700            | 244120         |
| 25  | 375            | 3.35            | 227.1          | 52100                 | 1200            | 86900            | 261120         |
| 26  | 395            | 3.35            | 237.1          | 56100                 | 1200            | 91100            | 278120         |
| 27  | 415            | 3.35            | 247.1          | 60100                 | 1200            | 95300            | 295120         |
| 28  | 435            | 3.35            | 257.1          | 64100                 | 1200            | 99500            | 312120         |
| 29  | 455            | 3.35            | 267.1          | 68100                 | 1200            | 103700           | 329120         |
| 30  | 475            | 3.35            | 277.1          | 72100                 | 1200            | 107900           | 346120         |
| 31  | 495            | 3.35            | 287.1          | 76100                 | 1200            | 112100           | 363120         |
| 32  | 515            | 3.35            | 297.1          | 80100                 | 1200            | 116300           | 380120         |
| 33  | 535            | 3.35            | 307.1          | 84100                 | 1200            | 120500           | 397120         |
| 34  | 555            | 3.35            | 317.1          | 88100                 | 1200            | 124700           | 414120         |
| 35  | 575            | 3.35            | 327.1          | 92100                 | 1200            | 128900           | 431120         |
| 36  | 595            | 3.35            | 337.1          | 96100                 | 1200            | 133100           | 448120         |
| 37  | 615            | 3.35            | 347.1          | 100100                | 1200            | 137300           | 465120         |
| 38  | 635            | 3.35            | 357.1          | 104100                | 1200            | 141500           | 482120         |
| 39  | 655            | 3.35            | 367.1          | 108100                | 1200            | 145700           | 500120         |
| 40  | 675            | 3.35            | 377.1          | 112100                | 1200            | 149900           | 517120         |
| 41  | 695            | 3.35            | 387.1          | 116100                | 1200            | 154100           | 534120         |
| 42  | 715            | 3.35            | 397.1          | 120100                | 1200            | 158300           | 551120         |
| 43  | 735            | 3.35            | 407.1          | 124100                | 1200            | 162500           | 568120         |
| 44  | 755            | 3.35            | 417.1          | 128100                | 1200            | 166700           | 585120         |
| 45  | 775            | 3.35            | 427.1          | 132100                | 1200            | 170900           | 602120         |
| 46  | 795            | 3.35            | 437.1          | 136100                | 1200            | 175100           | 619120         |
| 47  | 815            | 3.35            | 447.1          | 140100                | 1200            | 179300           | 636120         |
| 48  | 835            | 3.35            | 457.1          | 144100                | 1200            | 183500           | 653120         |
| 49  | 855            | 3.35            | 467.1          | 148100                | 1200            | 187700           | 670120         |
| 50  | 875            | 3.35            | 477.1          | 152100                | 1200            | 191900           | 687120         |
| 51  | 895            | 3.35            | 487.1          | 156100                | 1200            | 196100           | 704120         |
| 52  | 915            | 3.35            | 497.1          | 160100                | 1200            | 200300           | 721120         |
| 53  | 935            | 3.35            | 507.1          | 164100                | 1200            | 204500           | 738120         |
| 54  | 955            | 3.35            | 517.1          | 168100                | 1200            | 208700           | 755120         |
| 55  | 975            | 3.35            | 527.1          | 172100                | 1200            | 212900           | 772120         |
| 56  | 995            | 3.35            | 537.1          | 176100                | 1200            | 217100           | 789120         |
| 57  | 1015           | 3.35            | 547.1          | 180100                | 1200            | 221300           | 806120         |
| 58  | 1035           | 3.35            | 557.1          | 184100                | 1200            | 225500           | 823120         |
| 59  | 1055           | 3.35            | 567.1          | 188100                | 1200            | 229700           | 840120         |
| 60  | 1075           | 3.35            | 577.1          | 192100                | 1200            | 233900           | 857120         |
| 61  | 1095           | 3.35            | 587.1          | 196100                | 1200            | 238100           | 874120         |
| 62  | 1115           | 3.35            | 597.1          | 200100                | 1200            | 242300           | 891120         |
| 63  | 1135           | 3.35            | 607.1          | 204100                | 1200            | 246500           | 908120         |
| 64  | 1155           | 3.35            | 617.1          | 208100                | 1200            | 250700           | 925120         |
| 65  | 1175           | 3.35            | 627.1          | 212100                | 1200            | 254900           | 942120         |
| 66  | 1195           | 3.35            | 637.1          | 216100                | 1200            | 259100           | 959120         |
| 67  | 1215           | 3.35            | 647.1          | 220100                | 1200            | 263300           | 976120         |
| 68  | 1235           | 3.35            | 657.1          | 224100                | 1200            | 267500           | 993120         |
| 69  | 1255           | 3.35            | 667.1          | 228100                | 1200            | 271700           | 1010120        |
| 70  | 1275           | 3.35            | 677.1          | 232100                | 1200            | 275900           | 1027120        |
| 71  | 1295           | 3.35            | 687.1          | 236100                | 1200            | 280100           | 1044120        |
| 72  | 1315           | 3.35            | 697.1          | 240100                | 1200            | 284300           | 1061120        |
| 73  | 1335           | 3.35            | 707.1          | 244100                | 1200            | 288500           | 1078120        |
| 74  | 1355           | 3.35            | 717.1          | 248100                | 1200            | 292700           | 1095120        |
| 75  | 1375           | 3.35            | 727.1          | 252100                | 1200            | 296900           | 1112120        |
| 76  | 1395           | 3.35            | 737.1          | 256100                | 1200            | 301100           | 1129120        |
| 77  | 1415           | 3.35            | 747.1          | 260100                | 1200            | 305300           | 1146120        |
| 78  | 1435           | 3.35            | 757.1          | 264100                | 1200            | 309500           | 1163120        |
| 79  | 1455           | 3.35            | 767.1          | 268100                | 1200            | 313700           | 1180120        |
| 80  | 1475           | 3.35            | 777.1          | 272100                | 1200            | 317900           | 1197120        |
| 81  | 1495           | 3.35            | 787.1          | 276100                | 1200            | 322100           | 1214120        |
| 82  | 1515           | 3.35            | 797.1          | 280100                | 1200            | 326300           | 1231120        |
| 83  | 1535           | 3.35            | 807.1          | 284100                | 1200            | 330500           | 1248120        |
| 84  | 1555           | 3.35            | 817.1          | 288100                | 1200            | 334700           | 1265120        |
| 85  | 1575           | 3.35            | 827.1          | 292100                | 1200            | 338900           | 1282120        |
| 86  | 1595           | 3.35            | 837.1          | 296100                | 1200            | 343100           | 1299120        |
| 87  | 1615           | 3.35            | 847.1          | 300100                | 1200            | 347300           | 1316120        |
| 88  | 1635           | 3.35            | 857.1          | 304100                | 1200            | 351500           | 1333120        |
| 89  | 1655           | 3.35            | 867.1          | 308100                | 1200            | 355700           | 1350120        |
| 90  | 1675           | 3.35            | 877.1          | 312100                | 1200            | 359900           | 1367120        |
| 91  | 1695           | 3.35            | 887.1          | 316100                | 1200            | 364100           | 1384120        |
| 92  | 1715           | 3.35            | 897.1          | 320100                | 1200            | 368300           | 1401120        |
| 93  | 1735           | 3.35            | 907.1          | 324100                | 1200            | 372500           | 1418120        |
| 94  | 1755           | 3.35            | 917.1          | 328100                | 1200            | 376700           | 1435120        |
| 95  | 1775           | 3.35            | 927.1          | 332100                | 1200            | 380900           | 1452120        |
| 96  | 1795           | 3.35            | 937.1          | 336100                | 1200            | 385100           | 1469120        |
| 97  | 1815           | 3.35            | 947.1          | 340100                | 1200            | 389300           | 1486120        |
| 98  | 1835           | 3.35            | 957.1          | 344100                | 1200            | 393500           | 1503120        |
| 99  | 1855           | 3.35            | 967.1          | 348100                | 1200            | 397700           | 1520120        |
| 100 | 1875           | 3.35            | 977.1          | 352100                | 1200            | 401900           | 1537120        |
| 101 | 1895           | 3.35            | 987.1          | 356100                | 1200            | 406100           | 1554120        |
| 102 | 1915           | 3.35            | 997.1          | 360100                | 1200            | 410300           | 1571120        |
| 103 | 1935           | 3.35            | 1007.1         | 364100                | 1200            | 414500           | 1588120        |
| 104 | 1955           | 3.35            | 1017.1         | 368100                | 1200            | 418700           | 1605120        |
| 105 | 1975           | 3.35            | 1027.1         | 372100                | 1200            | 422900           | 1622120        |
| 106 | 1995           | 3.35            | 1037.1         | 376100                | 1200            | 427100           | 1639120        |
| 107 | 2015           | 3.35            | 1047.1         | 380100                | 1200            | 431300           | 1656120        |
| 108 | 2035           | 3.35            | 1057.1         | 384100                | 1200            | 435500           | 1673120        |
| 109 | 2055           | 3.35            | 1067.1         | 388100                | 1200            | 439700           | 1690120        |
| 110 | 2075           | 3.35            | 1077.1         | 392100                | 1200            | 443900           | 1707120        |
| 111 | 2095           | 3.35            | 1087.1         | 396100                | 1200            | 448100           | 1724120        |
| 112 | 2115           | 3.35            | 1097.1         | 400100                | 1200            | 452300           | 1741120        |
| 113 | 2135           | 3.35            | 1107.1         | 404100                | 1200            | 456500           | 1758120        |
| 114 | 2155           | 3.35            | 1117.1         | 408100                | 1200            | 460700           | 1775120        |
| 115 | 2175           | 3.35            | 1127.1         | 412100                | 1200            | 464900           | 1792120        |
| 116 | 2195           | 3.35            | 1137.1         | 416100                | 1200            | 469100           | 1809120        |
| 117 | 2215           | 3.35            | 1147.1         | 420100                | 1200            | 473300           | 1826120        |
| 118 | 2235           | 3.35            | 1157.1         | 424100                | 1200            | 477500           | 1843120        |
| 119 | 2255           | 3.35            | 1167.1         | 428100                | 1200            | 481700           | 1860120        |
| 120 | 2275           | 3.35            | 1177.1         | 432100                | 1200            | 485900           | 1877120        |
| 121 | 2295           | 3.35            | 1187.1         | 436100                | 1200            | 489900           | 1894120        |
| 122 | 2315           | 3.35            | 1197.1         | 440100                | 1200            | 494100           | 1911120        |
| 123 | 2335           | 3.35            | 1207.1         | 444100                | 1200            | 498300           | 1928120        |
| 124 | 2355           | 3.35            | 1217.1         | 448100                | 1200            | 502500           | 1945120        |
| 125 | 2375           | 3.35            | 1227.1         | 452100                | 1200            | 506700           | 1962120        |
| 126 | 2395           | 3.35            | 1237.1         | 456100                | 1200            | 510900           | 1979120        |
| 127 | 2415           | 3.35            | 1247.1         | 460100                | 1200            | 515100           | 1996120        |
| 128 | 2435           | 3.35            | 1257.1         | 464100                | 1200            | 519300           | 2013120        |
| 129 | 2455           | 3.35            | 1267.1         | 468100                | 1200            | 523500           | 2030120        |
| 130 | 2475           | 3.35            | 1277.1         | 472100                | 1200            | 527700           | 2047120        |
| 131 | 2495           | 3.35            | 1287.1         | 476100                | 1200            | 531900           | 2064120        |
| 132 | 2515           | 3.35            | 1297.1         | 480100                | 1200            | 536100           | 2081120        |
| 133 | 2535           | 3.35            | 1307.1         | 484100                | 1200            | 540300           | 2098120        |
| 134 | 2555           | 3.35            | 1317.1         | 488100                | 1200            | 544500           | 2115120        |
| 135 | 2575           | 3.35            | 1327.1         | 492100                | 1200            | 548700           | 2132120        |
| 136 | 2595           | 3.35            | 1337.1         | 496100                | 1200            | 552900           | 2149120        |
| 137 | 2615           | 3.35            | 1347.1         | 500100                | 1200            | 557100           | 2166120        |
| 138 | 2635           | 3.35            | 1357.1         | 504100                | 1200            | 561300           | 2183120        |
| 139 | 2655           | 3.35            | 1367.1         | 508100                | 1200            | 565500           | 2199120        |
| 140 | 2675           | 3.35            | 1377.1         | 512100                | 1200            | 569700           | 2216120        |
| 141 | 2695           | 3.35            | 1387.1         | 516100                | 1200            | 573900           | 2233120        |
| 142 | 2715           | 3               |                |                       |                 |                  |                |



| S   | $I_R$ | $E_2$ | $I_m$ | $E I_m$ | $.087 I_2^2$ | VARP | VAR   | IL |
|-----|-------|-------|-------|---------|--------------|------|-------|----|
|     | 120   | 121   | 28.4  | 3385    | 1.5          | 3385 | 10236 |    |
|     | 123   | 123   | 28.7  | 3410    | 6.2          | 3412 | 10353 |    |
|     | 12.7  | 124   | 29.0  | 3445    | 14.0         | 3451 | 10482 |    |
|     | 16.9  | 125   | 29.2  | 3480    | 24.8         | 3484 | 10590 |    |
|     | 21.1  | 126   | 29.5  | 3505    | 39.6         | 3517 | 10727 |    |
|     | 25.6  | 127   | 30.1  | 3540    | 78.6         | 3584 | 11067 |    |
|     | 32.4  | 133   | 31.0  | 3610    | 156          | 3714 | 11628 |    |
|     | 51.0  | 137   | 32.0  | 3720    | 226          | 4064 | 12198 |    |
| -15 | 3.8   | 140   | 32.6  | 3840    | 353          | 4163 | 12790 |    |
| -15 | 151   | 143   | 33.4  | 3910    | 417          | 4177 | 13560 |    |
|     |       | 146   | 34.0  | 4010    | 634          | 4714 | 14150 |    |
|     |       | 150   | 35.0  | 4080    | 814          | 5014 | 15050 |    |
| -5  |       | 154   | 35.9  | 4200    | 1010         | 5164 | 15960 |    |
| -15 | 158   | 156   | 36.1  | 4310    | 1218         | 5584 | 16740 |    |
|     |       | 162   | 36.0  | 4470    | 1462         | 5940 | 18190 |    |
|     |       | 162   | 36.1  | 4560    | 1718         | 615  | 18730 |    |
|     |       | 166   | 37.1  | 4660    | 1975         | 6465 | 19550 |    |
|     |       | 169   | 41.1  | 4710    | 2665         | 7170 | 20160 |    |
|     |       | 172   | 46.1  | 4860    | 310          | 7804 | 2150  |    |



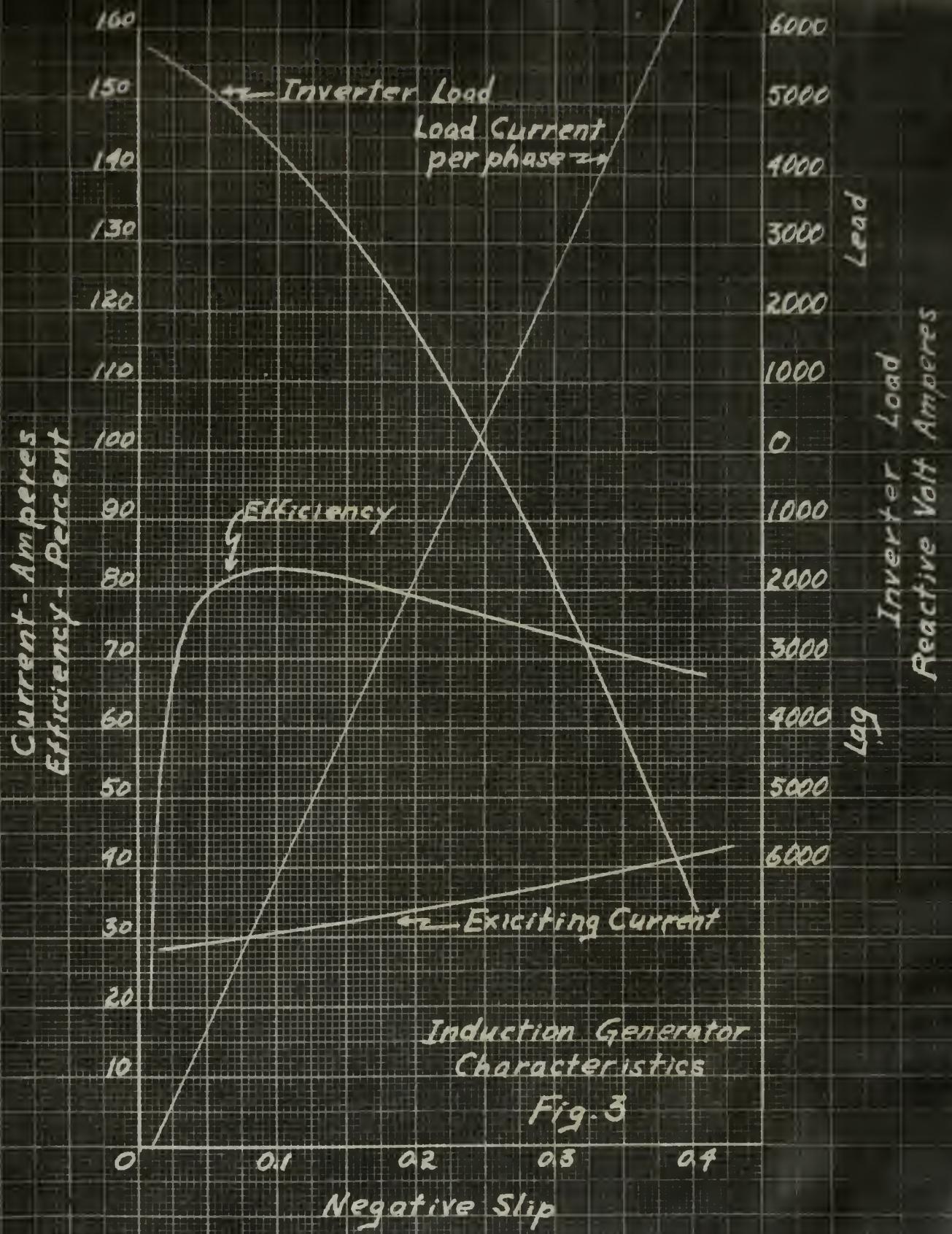


Fig. 3







At this point, the constant frequency source must still supply 16,500 reactive volt amperes at full load and 20000 at 50% overload. If three condensers of 49 microfarads each are connected in delta across the terminals of the induction generator its requirements become 5000 VA leading at no load, zero at full load and 5000 VA lagging at 50% overload. These condensers should not weigh more than six pounds or occupy more than 11 cubic inches.

From the design of the machine it was found that as a motor this particular machine developed a starting torque of 140 ft-lbs and had a rated torque of 52.1 ft-lbs at 5400 rpm. Such a motor would be excellent for use as a starter motor for aircraft engines. The displacement of the d.c. starter motor represents a saving of approximately 90 lbs. on each engine.



## CHAPTER IV

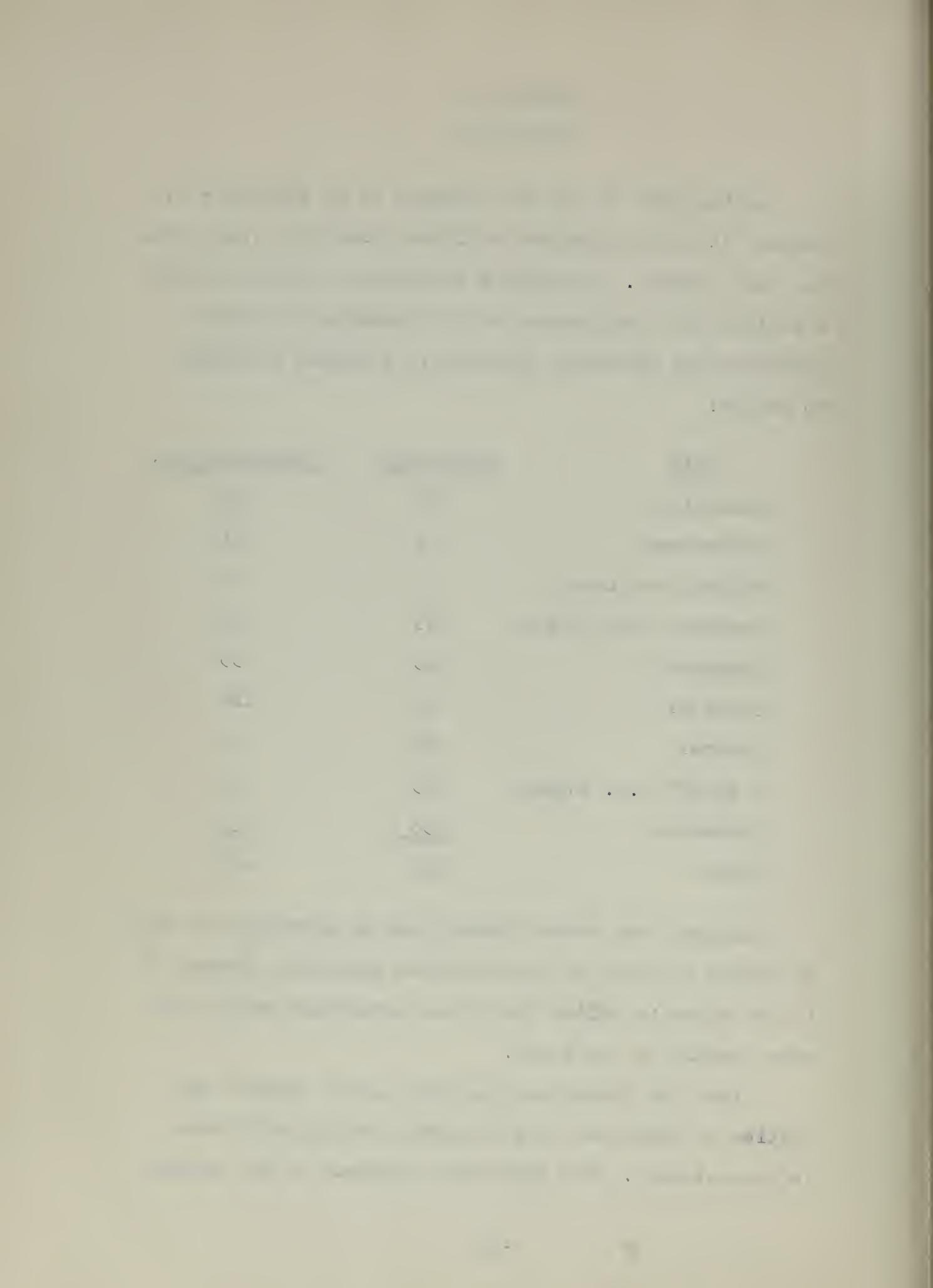
## CONCLUSION

In the case of any new proposal it is desirable to compare it with equivalent equipment presently fulfilling the same purpose. Assuming a theoretical aircraft having a maximum load requirement of 40 kilowatts from each generator the following results are obtained in regard to weight:

| <u>Unit</u>                      | <u>Alternator</u> | <u>Induction Gen.</u> |
|----------------------------------|-------------------|-----------------------|
| Generator                        | 120               | 98                    |
| Condensers                       | 0                 | 21                    |
| Voltage regulator                | 9                 | 0                     |
| Constant Speed Drive             | 75                | 75                    |
| Conductor                        | 45                | 35                    |
| Inverter                         | 40                | 120                   |
| Starter                          | 85                | 0                     |
| 4 KW 28 <sup>V</sup> d.c. supply | 25                | 25                    |
| Batteries                        | <u>55</u>         | <u>55</u>             |
| Total                            | 454               | 429                   |

Although the above figures show an advantage of only 25 pounds in favor of the induction generator system, it is the author's belief that other advantages weigh even more heavily in its favor.

Since the induction generator has no brushes the problem of brush and slip ring wear at high altitudes is non-existent. The inverters necessary to the system



could be located in a pressurized section of the fuselage so as to reduce this problem in that equipment.

Since power is more easily sensed than frequency the control of the variable speed drive could be simplified. Small variations in generator speed will produce changes in load distribution but no circulating currents will exist unless a machine drops to or below synchronous speed.

The induction machine being basically a simpler more rugged machine than the synchronous type it should be both cheaper to build and more durable in service.



## APPENDIX

The following formulae were used in the design of this machine:

$$E = 8.06 \text{ kbkpVlNB } 10^{-8}$$

$$\Delta = NI \div \pi d$$

$$\lambda_p = d \div 2p$$

$$\lambda_t = d \div Nt$$

$$Ph' = 2 \frac{n}{100} (Bm^{10^{-5}}) 1.6$$

$$Pe'' = (n Bm t 10^{-5})^2$$

$$Ii'' = 1 + 1.5 Acp \lambda_p$$

$$Hl = (1 + 0.02v) \div 60$$

$$Tl = P1 \div H_l S_l$$

$$Pk2 = 7465 HF \div N$$

$$\Delta = 1.23 \cdot 10^{-8} \div kp Bd^2 l$$

$$Ib = 1.01 \Delta \lambda_{tl}$$

$$Iba = Ib \div 1.11$$

$$Ir = Nt2 Iba \div 4 \cdot 2 P$$

$$R_2 = Pk2 \div (I R p.f.)^2$$

$$f = 0.6 + 1.47 \log (S0l \div 2)$$

$$t1 = ttl + 2 f, \delta$$

$$a1 = t1 \div \lambda_{t1}$$

$$a2 = t2 \div \lambda_{t2}$$

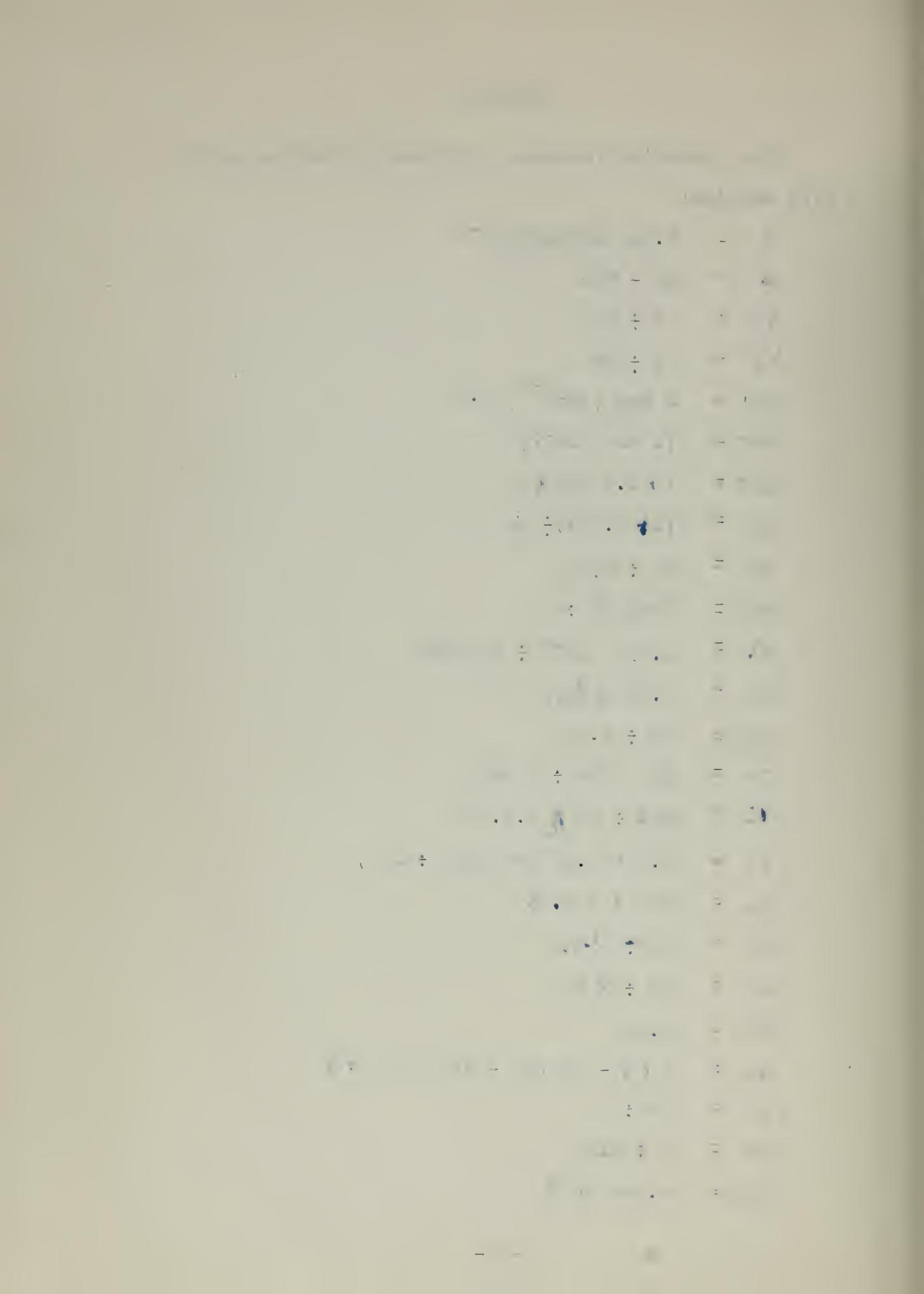
$$Kl = A \cdot A2$$

$$le = 1 + \delta - Nd (Wa - 2fd) = 1 + \delta$$

$$Kd = le \div 1$$

$$Bc = B \div Kl Kd$$

$$ATg = 0.626 Bc \delta$$

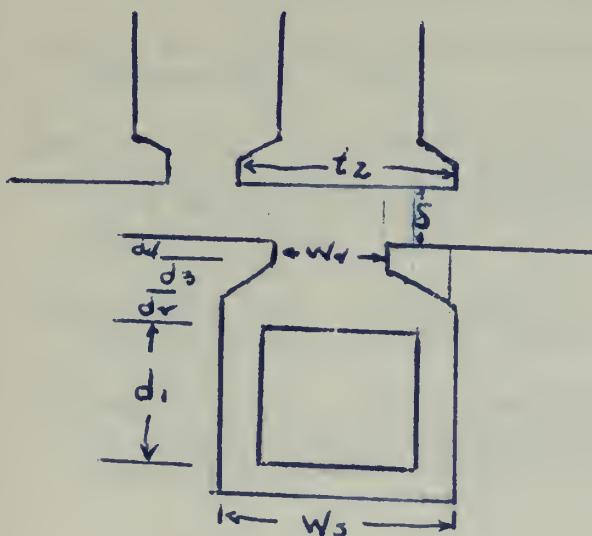


$$\chi_1 = 2\pi f 10^{-8} k_B k_p p S_1 C_1^2 N \Phi_1 l$$

$$N \Phi_1 = 3.19 \left[ \frac{d_1}{3w_3} + \frac{d_2}{w_3} + \frac{2d_3}{w_4+w_3} + \frac{d_4}{w_4} \right] + 3.14 \frac{t_1 - w_4}{6s} + \frac{l_c}{l} \left[ .146 \log \frac{\pi l_c}{U} + 0.064 \right]$$

$$\chi_2 = 2\pi f 10^{-8} k_B k_p p S_2 C_2^2 N \Phi_2 l \left[ \frac{C_1 S_1}{C_2 S_2} \right]^2$$

$$N \Phi_2 = 3.19 \left[ \frac{d_1}{3w_3} + \frac{d_2}{w_3} + \frac{2d_3}{w_4+w_3} + \frac{d_4}{w_4} \right] + 3.14 \frac{t_1 - w_4}{6s} + \frac{l_c}{l} \left[ .146 \log \frac{\pi l_c}{U} + 0.064 \right]$$



p = no of poles

s = slots /phase/ pole

C = conductors/slot

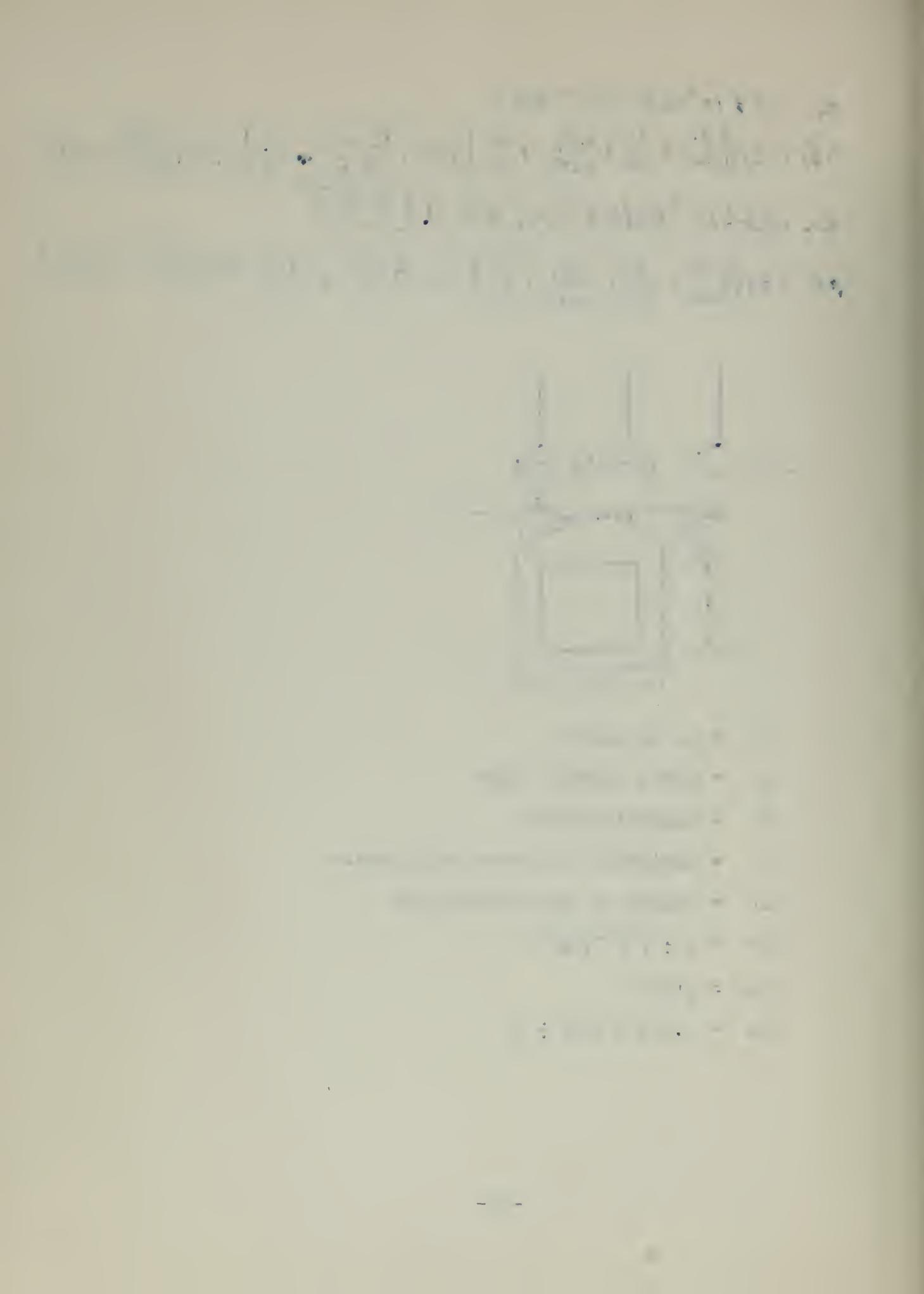
U = perimeter of phase belt bundle

$l_c$  = length of end connections

$$I_s = E \div \sqrt{r^2 + x^2}$$

$$T_{ss} = p' I_s^2$$

$$T_s = 0.117 p T_{ss} \div n$$



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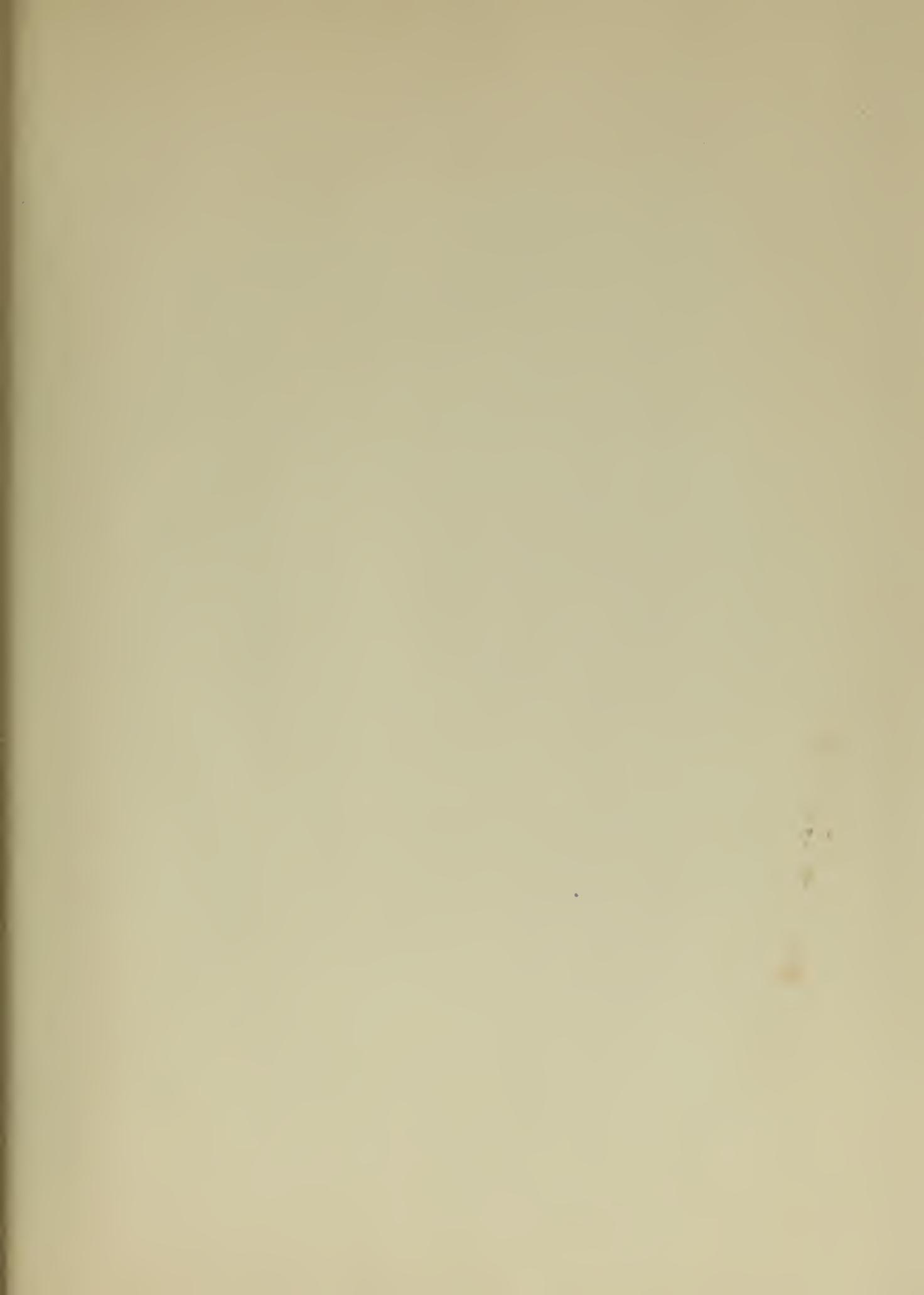




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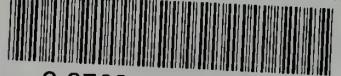
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